Mostly Functional C#

a.k.a. Taming Side Effects (TSE)

Midori

Joe Duffy, Midori

August, 2009

Background, Aka Why?

- My (recent) history:
  - "No more free lunch" in 2004, on the CLR Team.
  - Software transactional memory in 2005.
  - Began Parallel LINQ (PLINQ) also in 2005.
  - Evolved into Parallel Extensions to .NET Framework (4.0) in 2007, served as lead / architect.
  - Shipping in Visual Studio 2010.
- And in the meantime, realized we need more fundamental changes to enable *safe* parallelism.
  - Began with "purely functional".
  - And evolved to "mostly functional" over past 1 ½ years.

Or, in the words of Simon Peyton Jones

- "[A] big programming-language theme over the next ten years will be mechanisms to restrict or control unrestricted side effects. … One way or another[,] we need to get a handle on those effects."

--- *Caging the Effects Monster: the next big challenge*, Simon Peyton Jones, QCon 2008

Talk Overview

- **What is Midori?**
- What is Mostly Functional C#?
  - Object Isolation
  - Other Features
- The Road Ahead: Reality Check
- Q & A

What is Midori?

- Systems incubation under Eric Rudder
- 75 people, almost entirely developers and architects
- New operating system (spawn of Singularity)
- New application programming model
- Large compiler effort
- Legacy free (mostly)

Key Midori Assumptions

- Cloud is integral
  - User-data in the cloud (partially)
  - Services in the cloud
- Clients are not simple
  - Multi-core and many-core
  - Rich functionality with local data
  - Multiple clients per person
- Clients are mobile
  - Occasionally-connected networks
  - High and variable latencies (e.g., network & memory)
  - Power management is essential
- Security, safety, and reliability are crucial

Key Midori Goals and Principles

- Refresh the software stack for modern issues
  - Existing OSes and app models are ~30 years old
- Reliability
  - Memory, type, **concurrency safety** guaranteed
  - "Correct by construction"
  - Responsiveness: "asynchonous everywhere"
- Security
  - Capability-based: no ACLs
  - "Secure by construction"
- Support using hundreds of cores well

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Design Approach

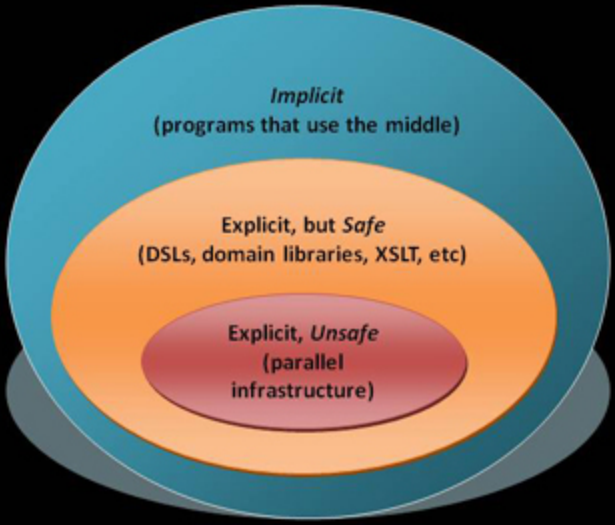
- A prototype extension of the C# language.
- Make functional programming in C# *the default*:
  - C# = { imperative + dynamic + ***functional*** }
  - Methods do not mutate existing state.
  - Immutable types are first class.
- Allow imperative programming where familiar, convenient, and/or more efficient:
  - This is still C#! Iteration, objects, etc.
  - State *can* be mutated, but only where declared.
- Why?
  - Deterministic, safe parallelism.
  - Robustness, reliability, and contracts.

Inspiration

- Haskell. 
  - They *can* do implicit parallelism.
  - The safety problem is solved:
    - We can only ever hope to do as good as them, but no better.
    - Parallelism is constrained by ***data dependence***.
    - Places emphasis on feedback directed optimizations.
- Launchbury, Jones, Wadler:
  - "Lazy functional state threads."
  - "Imperative functional programming."

```
swap :: MutVar s a -> MutVar s a -> ST s ()
swap v w = readVar v    `thenST` \a ->
           readVar w    `thenST` \b ->
           writeVar v b `thenST_`
           writeVar w a
```

A Landscape of Concurrency



Cut to the Chase

- Mode #1: Auto-parallelize, when safe:
  - ```
    var q = from x in xs.AutoParallel()
            where (x & 1) == 0
            select x * 0.03f;
    ```
  - ```
    int c = 0.03f;
    var q = from x in xs.AutoParallel()
            where (x & 1) == 0
            select x * (c += 0.05f);
    ```
- Mode #2: Compiler error, when unsafe:
  - ```
    var q = from x in xs.AsParallel()
            where (x & 1) == 0
            select x * 0.03f;
    ```
  - ```
    int c = 0.03f;
    var q = from x in xs.AsParallel()
            where (x & 1) == 0
            select x * (c += 0.05f);
    ```

No side-effects, runs in parallel

Has side-effect, runs sequentially

No side-effects, compiles and runs in parallel

Has side-effect, fails to compile

Feature List (Big-to-Small)

- Object isolation model
- Immutable types
- Non-nullability
- Linear types
- “where T : *S* { … }” specialization / matching
- Async “future” lifting
- Tuples

A Word of Caution

- ***Everything*** in MfC# is an experiment.
  - No commitment to add it to C#, in any way.
  - In the process of adopting it in Midori.
  - See how it goes, and let DevDiv know.
- http://toolbox/ release is coming soon…
  - In the next couple weeks.
  - Complete with a "Programming Guide" overview.
  - And prototype of "safe data parallel" APIs.
  - Join 'tse' alias for updates / announcements.

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Key Idea: Object Isolation

- No mutable statics.
- Permission tagged references:
  - `writable Foo wFoo`: all state in the graph can be read/written.
  - `readable Foo rFoo`: all state in the graph can be read.
  - `immutable Foo iFoo`: only **readonly** fields in the graph can be read.
- Implicit coercion: writable > readable > immutable.
- Default if unstated:
  - Usually **readable** (functional by default).
  - Sometimes **immutable** (for references of immutable types).
- Appears in any position (see next slide).

Where Can Permissions Appear?

- Fields:
  - `class C { public writable T m_f; }`
- Local variables:
  - `public isolated void M() { writable T obj = …; …; }`
- Formal parameters:
  - `public isolated void M(writable T obj) { … }`
- Return parameters:
  - `public isolated writable T M() { …}`
- The hidden 'this' parameter for instance methods:
  - `public isolated void M() writable { … }`

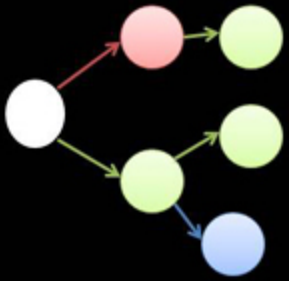
- (The same locations for isolated delegates.)

- Actual parameters for generics:
  - `List<writable T> list = new List<writable T>();`

Permission combining

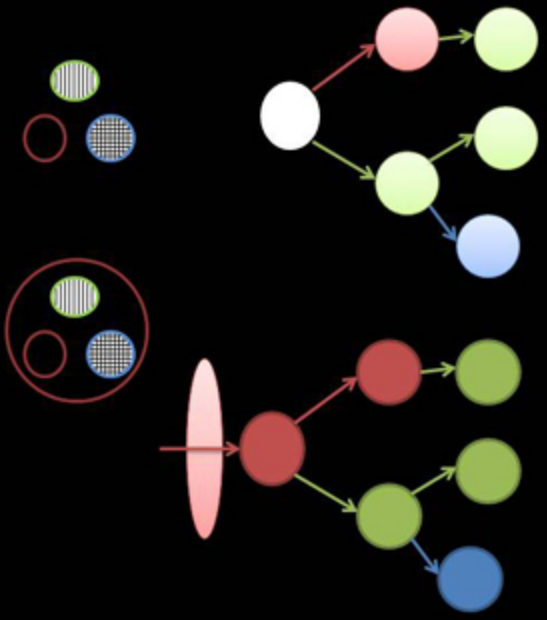
- Obtaining a field value combines permissions:
  - Accessing a field yields the least permissive of the field and the source reference.
  - E.g., writable U via a readable T => readable U.
- Ensures “deepness”. So:
  - immutable Foo f: no mutable state accessible via f.
- Generics similarly combine between generic and instantiation.
  - E.g., writable T will yield least permissive between writable and concrete instantiation.

An Object Graph



- Red lens preserves all colors.
- Green lens filters out red.
- Blue lens makes everything blue.

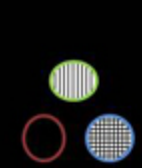
Writable Object Graph

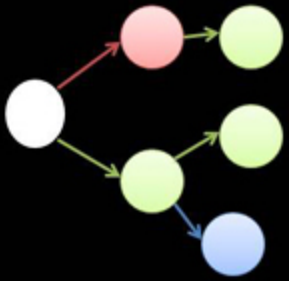


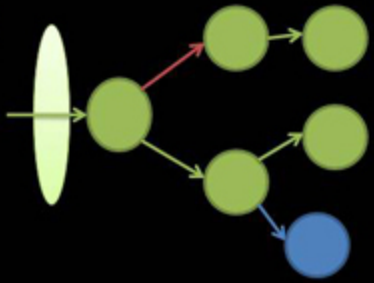

```
writable Foo wObj = new Foo();
```

- **Red lens preserves all colors.**
- Green lens filters out red.
- Blue lens makes everything blue.

Readable Object Graph







```
Foo rObj = wObj;
```

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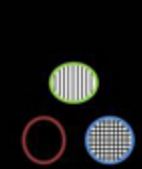
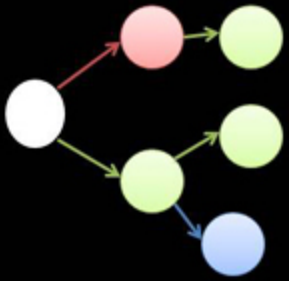
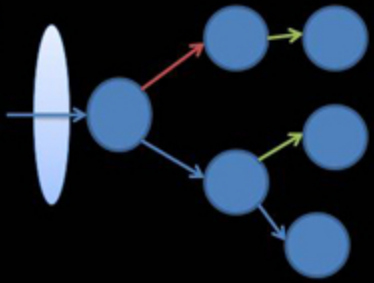
Immutable Object Graph








```
immutable Foo iObj = rObj;
```

- Red lens preserves all colors.
- Green lens filters out red.
- **Blue lens makes everything blue.**

But Wait! There's More!

- Co- and contravariant permissions on override.
  - `public abstract class A { abstract immutable T M() writable; }`
  - `public class B : A { override /*readable*/ T M() immutable; }`
- Local variable permission inference.
  - `writable IEnumerator<T> e = d.GetEnumerator();`
  - `var e = d.GetEnumerator();`
- Anonymous method inference.

```
public delegate void D(T e);
public isolated delegate void IsoD(T e);

void M(D d);
void M(IsoD d);
void f() {}
isolated void g() {}

m(() => f()); // OK! Binds to M(D);
m(() => g()); // OK! Binds to M(IsoD);
```

Example: String Concatenation

- No new annotations:

```
public string Concat(string[] ss) {
    var sb = new StringBuilder();
    foreach (string s in ss)
        sb.Append(s);
    return s.ToString();
}
```

- Relies on defaults; expanded code is:

```
public immutable string Concat(readable string[immutable] ss) {
    writable StringBuilder sb = new StringBuilder();
    foreach (immutable string s in ss)
        sb.Append(s);
    return s.ToString();
}
```

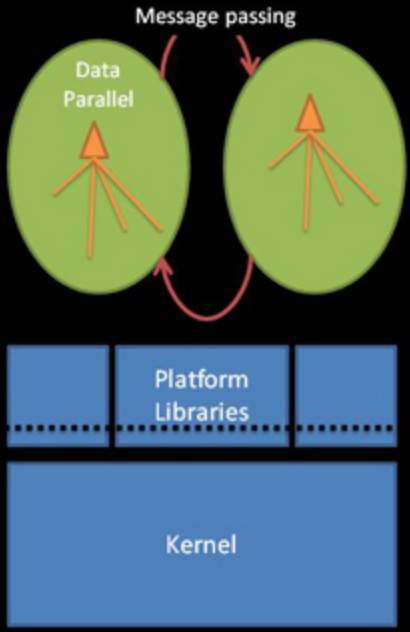
Example: ICollection<T>

```
interface ICollection<T> {
    bool Contains();
    int IndexOf(T item);
    void CopyTo(writable T[] array, int arrayIndex);
    int Count { get; }
    bool IsReadOnly { get; }

    void Add(T item) writable;
    void Clear() writable;
    bool Remove(T item) writable;
}
```

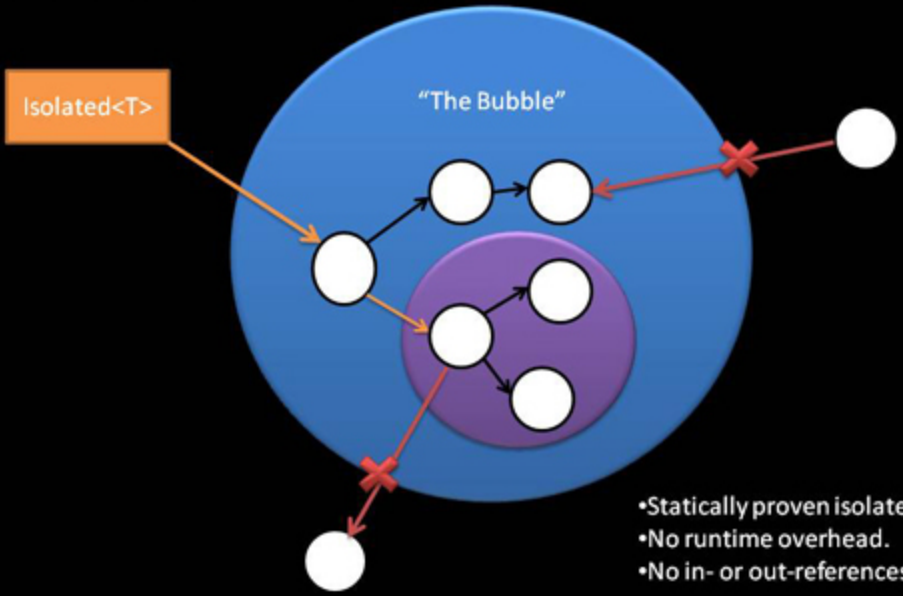
Isolation in Midori

- Everything above the line uses TSE by default.
  - No freethreading, memory models.
  - Small # of abstractions that don't.
  - E.g., Lazy<T>, data parallel, etc.
  - Below the line is opt-in.
- Single threaded processes.
  - Communicate via message passing.
  - Internal data parallelism.
  - …But only the safe kind.



Isolated Object Graphs

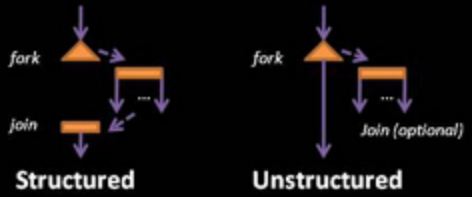
```
delegate T PureFunc<T>() immutable;
```



- Statically proven isolated.
- No runtime overhead.
- No in- or out-references.

Safe Parallelism

- Concurrency ground rules:
  - No two threads ever see the same object as **writable** *at once*.
  - No thread sees an object as **readable** while another sees it as **writable**.
  - An object can always be seen as **immutable**.
- Two categories:



- Structured is split into two subcategories:
  - In-place updates: e.g., arrays, isolated object graphs.
  - Functional: e.g., LINQ-like data comprehensions.

A Few Examples

- Parallel Fibonacci:

```
public static int Fib(int n) {
    if (n <= 1) return 1;
    var result = Parallel.Invoke(() => Fib(n - 2), () => Fib(n - 1));
    return result.Item1 + result.Item2;
}
```

- LINQ-like comprehensions:

```
public static int[] InverseOdds(int[] input) {
    return input.AsParallel().
        Filter(x => (x & 1) == 1).
            Map(x => -x).
            Execute();
}
```

A Few Examples

- Parallel Fibonacci:

```
public static int Fib(int n) {
    if (n <= 1) return 1;
    var result = Parallel.Invoke(() => Fib(--(--n))), () => Fib(--n));
    return result.Item1 + result.Item2;
}
```

- LINQ-like comprehensions:

```
public static int[] InverseOdds(int[] input) {
    return input.AsParallel().
        Filter(x => (x & 1) == 1).
            Map(x => --input[0]).
            Execute();
}
```

Any race conditions are flagged as compile-time errors.

error cs20004: Object only has 'readable' access; storing to a field requires 'writable'

Benevolent Side Effects

- *"[T]here is no one right way of writing every program and a language designer has no business of trying to force programmers to use a particular style. The language designer does, on the other hand, have an obligation to encourage and support a variety of styles and practices that have proven effective and to provide language features and tools to help programmers avoid the well known traps and pitfalls."*

  --- Bjarne Stroustrup,
  A History of C++: 1979—1991

Benevolent Side Effects

- System abstractions must lie sometimes:
  - No mutable statics? `public static Lazy<Foo> s_foo = new Lazy<Foo>(…);`
- So long as they *dynamically* preserve the safety, **unstrict** can be used:

```
public class Lazy<T> where T : class {
    private T m_value;
    private LazyFunc<T> m_func = …;
    private object m_lock = new object();

    public T Value {
        get {
            if (m_value == null)
                unstrict {
                    lock (m_lock)
                        if (m_value == null)
                            m_value = m_func();
                }
            return m_value;
        }
    }
}
```

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Immutable Types

- Marking any type as immutable:
  - All fields are **readonly** (unless marked **mutable**).
  - "Shallow" immutability.
- Property initializers:
  -
```
immutable class ImmStack<T> {
    private static ImmStack<T> Empty = new ImmStack<T>();
    public ImmStack<T> Head { get; } = Empty;
    public T Value { get; }
    …
}
```
- Deep can be obtained with immutable refs.

Non-Nullability

- "I call it my billion-dollar mistake. It was the invention of the null reference in 1965."
  -- Tony Hoare,
  Historically bad ideas, QCon London 2009
- Only T? references may be assigned **null**.
  - Unification of nullable<T> for ref and val types.
  - T? coercable to T, but entails a dynamic null check.
- A lot like Spec# non-nullable types, T!, but the default is flipped.

Linear Types

- A reference can be marked linear:
  - `linear<Graph<T>> graph = …;`
  - No aliases allowed ~= exclusive ownership.
- Type must be marked linearizable:
  - No aliasing of 'this' during execution.
  - All fields are themselves linear.
- Allows:
  - Handoff of writable linear objects:
    - ```
      writable linear<T> v = …;
      Task<int> t = new Task<int>(o => o.Mutate(), v);
      ```
  - Update in-place of linear objects:
    - ```
      Writable linear<T> vs[writable] = …;
      Parallel.ForEach(vs, v => v.Mutate());
      ```

Specialization / Matching

- Static callsite specialization:
  - Pattern matching.
  - More efficient code generation.
  - E.g.,

```
public double Sum<T>(T x)
{
    where T : int, double {
        return x;
    }
    …
    else where T : List<U> {
        return Sum(x.Car) + Sum(x.Cdr);
    }
    else {
        return 1.0;
    }
}
```

Async “Future” Lifting

- We use “promises” in Midori for async.
  - Any value can be a promise for a value.
  - Pipeline operations against it; or, invoke When and, in the callback, you can access the value.
- Any T can be marked async<T>:
  - `async<T> a <- Remote.Call();`
  - `async<U> b <- a.Foo(); // Pipeline.`
  - `async<V> c <- b.When(v => … v …); // When.`
- Notice that <- is used as “message send”.

Tuples

- Syntactic sugar for tuples (in .NET 4.0).
  - Usable as “anonymous” types that appear publicly.
- A first class type:
  - (int, DateTime) ~= Tuple<int, DateTime>
  - public void M((int, DateTime) v) { ... V.First ...);
- And special initializer syntax:
  - var t = new () { 42, “hello”, 0.1f };
  - t is of type (int, string, float) ~= Tuple<int, string, float>

Addressing Legacy (and Reality)

- Bifurcation:
  - **nonstrict** methods *don't* abide by the rules.
  - **strict** methods *do*.
    - And only call other strict methods.
- Downward separation:
  - Legacy (nonstrict) can call into new code (strict).
  - Once you're in, you can't get out.
- "We don't make things worse".
  - Pass an object as writable to concurrent strict methods.
  - You had a race before. No worse.
  - But we give you a pocket of safety: no mistakes.

Current Status

- Initial phase ("is it too crazy to work?"):
  - Integration with Axum's type system (via Q).
  - Custom attributes + FxCop verification done.
    - `[Writable] void Foo([Writable] Bar b) { … }`
  - Prototypes of:
    - Midori base class libraries.
    - Safe data parallel programming model.
- Next phase ("get real"):
  - C# 3.5 compiler work 90% done.
    - Aim to wrap up in a few weeks; after that: all of Midori uses it.
    - Will go up on http://toolbox/.
  - Data parallelism, race free finalization, message passing.
  - …implicit in several areas (e.g., LINQ, Array.Sort).

The Road Ahead: Challenges

- Is opt-in to imperative mutation cumbersome?
  - **writable** by default makes it easier.
  - But relies on abstinence to go functional.
  - *The bet*: mostly functional is the sweet spot; hence less ceremony.
- Safe parallelism is sometimes limiting:
  - No ad-hoc inter-thread communication.
  - *The bet:* race freedom is well worth it.
- What to do with the existing libraries…
  - Slowly move them on to the new plan?
  - But what about interfaces, events, callbacks, …
  - And other languages who don't care: Python, Ruby, …

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Q & A

- http://toolbox/mfcsharp/
- http://midori/

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- Static callsite specialization:
  - Pattern matching.
  - More efficient code generation.
  - E.g.,

```
public double Sum<T>(T x)
{
    where T : int, double {
        return x;
    }
    …
    else where T : List<U> {
        return Sum(x.Car) + Sum(x.Cdr);
    }
    else {
        return 1.0;
    }
}
```